A few key ideas from RF1 & RF2 town-hall

Summarized by Marina Artuso

RF1- topical group conveners Angelo Di Canto and Stefan Meinel

RF2- topical group conveners Emilie Passemar and Evgueni Goudzovski

For more information

https://snowmass21.org/rare/start
https://snowmass21.org/rare/weakbc
https://snowmass21.org/rare/weaksud

Including calendar of events

The big picture

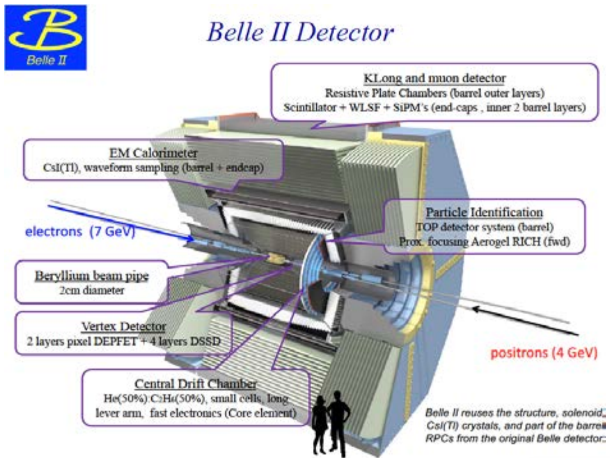
"there is a crack in everything [even SM]
That's how the light gets in"

[Leonard Cohen]

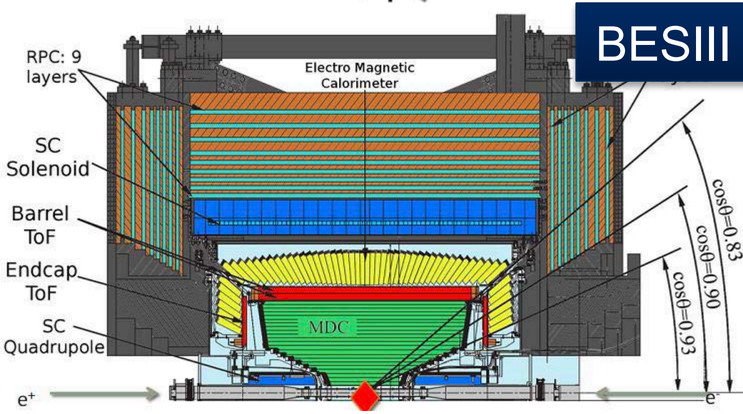
We are investigating:

- The crack through precision tests of the SM
- The crack through rare processes

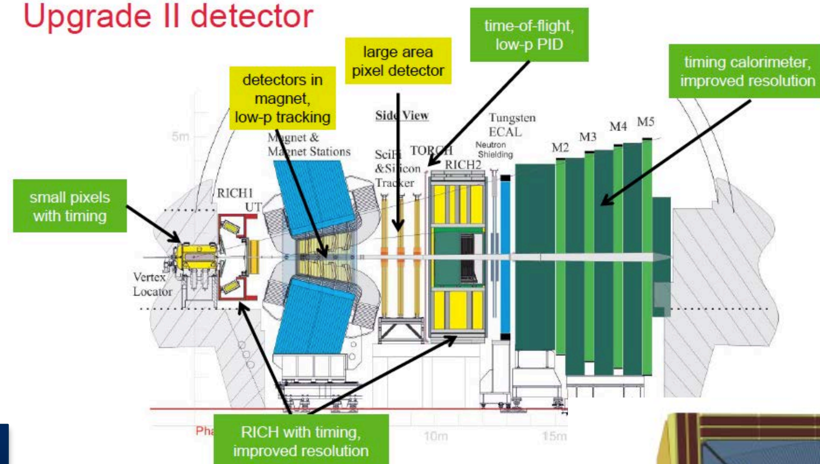
RF1-Experimental approach to heavy-quark studies



BESIII

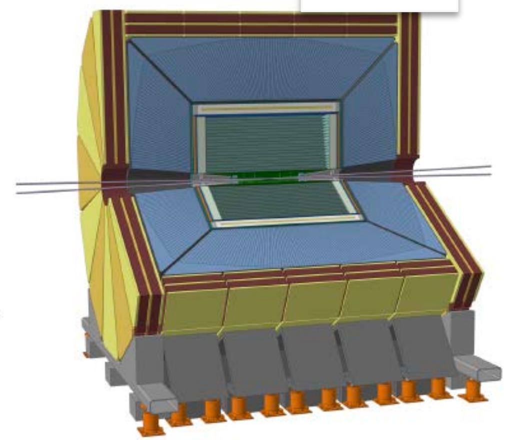


LHCb
Upgrade II detector



Also ATLAS/CMS NOW ⇒HL-LHC

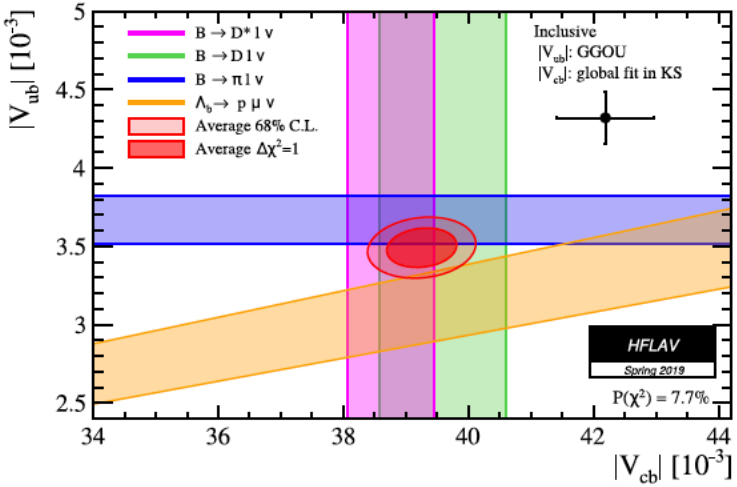
FCC-EE

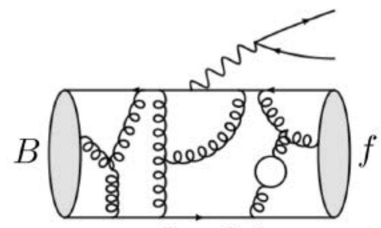


IDEA design

RF1- heavy quarks –Challenges to the SM

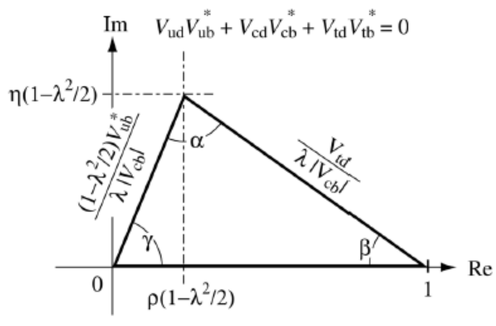
Tension between different determinations
of CKM parameters

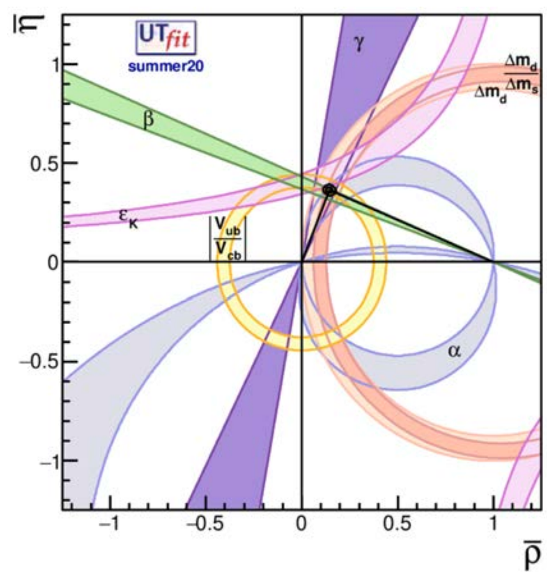




→ Non-perturbative QCD, i.e. difficult to compute

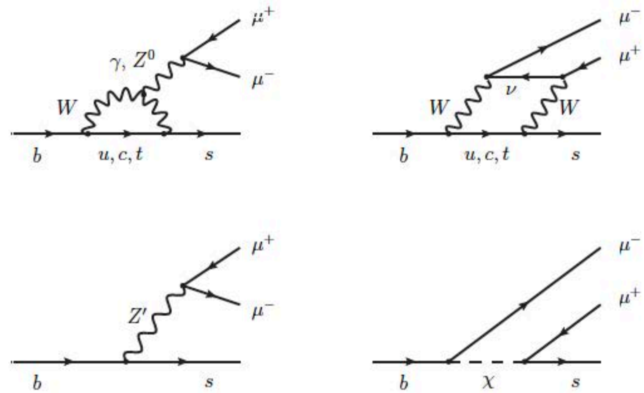
(Lattice QCD, QCD factorisation, Light-cone sum rules...)



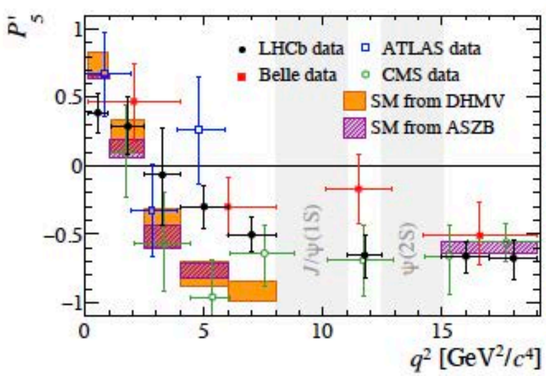


RF1- heavy quarks Indirect evidence for new physics

$b \to s\ell^+\ell^-$

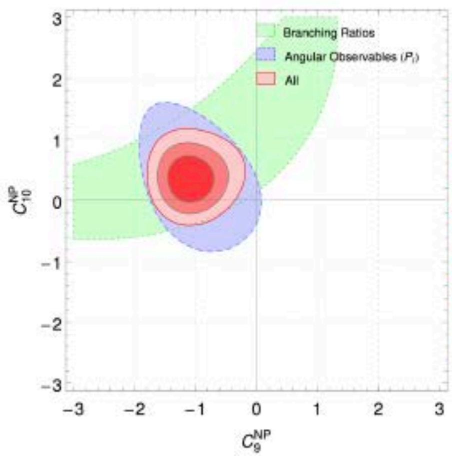


Differential distributions



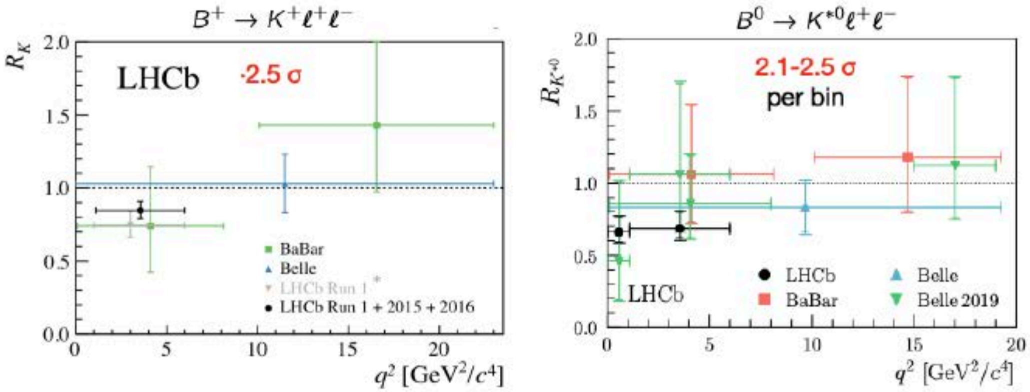
[PLB 781 (2018) 517]
[JHEP 10 (2018) 047]
[PRL 118 (2017) 111801]
[JHEP 02 (2016) 104]

EFT analysis



[JHEP06 (2016) 092]

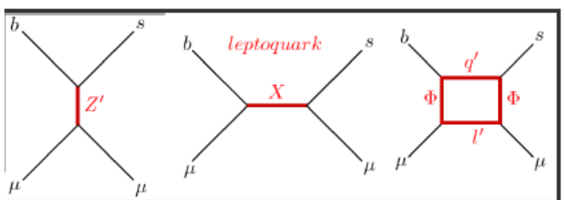
RF1 – LVU violation?



[LHCb, PRL 113 (2014) 151601]
[LHCb, JHEP 08 (2017) 055]
[BaBar, PRD 86 (2012) 032012]
[LHCb, PRL 122 (2019) 191801]
[Belle, PRL 103 (2009) 171801]
[Belle, arXiv:1904.02440]

G.Isidori, FPCP 2020: correlations among b→s(d)ll' within the U(2)-based EFT

	μμ (ee)	ττ	νν	τμ	μe
b → s	R_K, R_{K^*} O(20%)	$B \to K^{(*)}\,\tau\tau$ → 100×SM	$B \to K^{(*)}\,\nu\nu$ O(1)	$B \to K\,\tau\mu$ → 10^{-6}	$B \to K\,\mu e$???
b → d	$B_d \to \mu\mu$, $B \to \pi\,\mu\mu$, $B_s \to K^{(*)}\,\mu\mu$ O(20%) [R_K=R_π]	$B \to \pi\,\tau\tau$ → 100×SM	$B \to \pi\,\nu\nu$ O(1)	$B \to \pi\,\tau\mu$ → 10^{-7}	$B \to \pi\,\mu e$???



Leptoquarks are color-triplet bosons that carry both lepton and baryon numbers

Lot of those models predict also LFV b→seμ, b→seτ,…

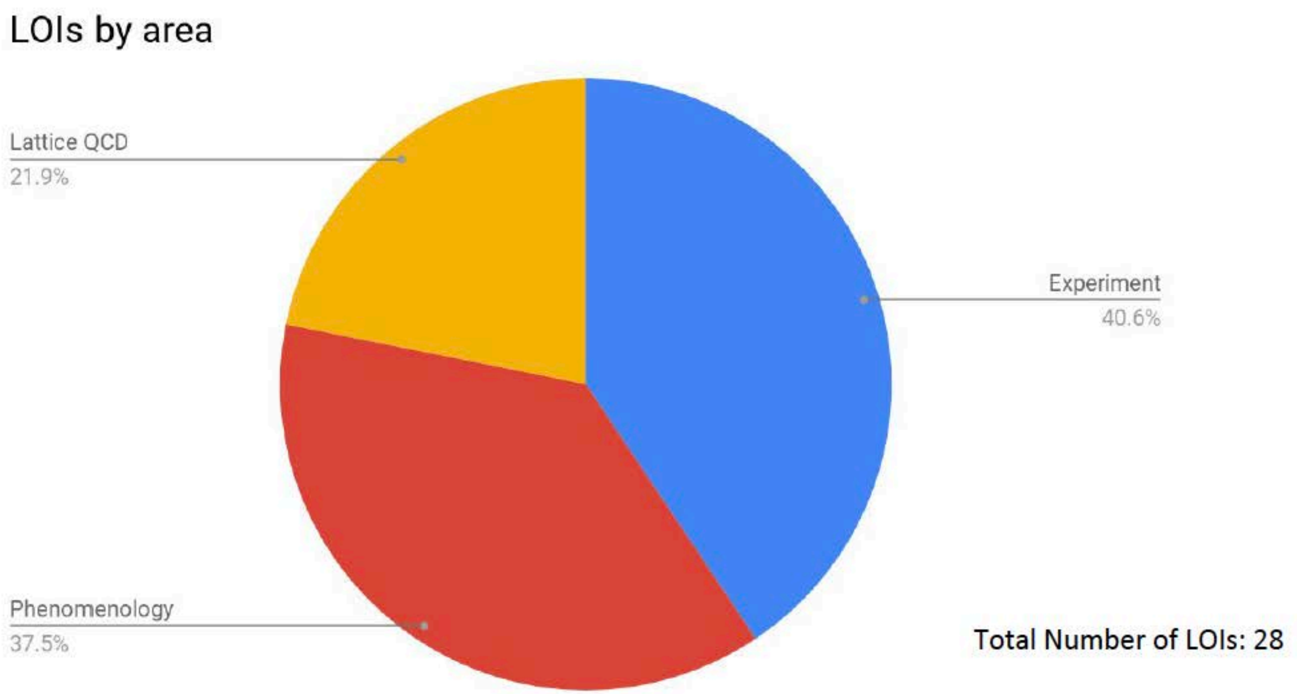
Theory connection

- Lattice QCD provides accurate calculations of several matrix elements needed to relate the hadron decays studied with the fundamental quantities sought for. [see also parallel session 124]

- Theoretical analyses of “anomalies” in model independent EFT fits investigates the general properties of the new physics. [hot topic in this TG and more broadly, see also parallel sessions 41,125]

- Phenomenological models weaving unexpected observations together (e.g. R-parity SUSY, leptoquark, Z’ ..) [see also parallel session 126]

Summary of LOIs

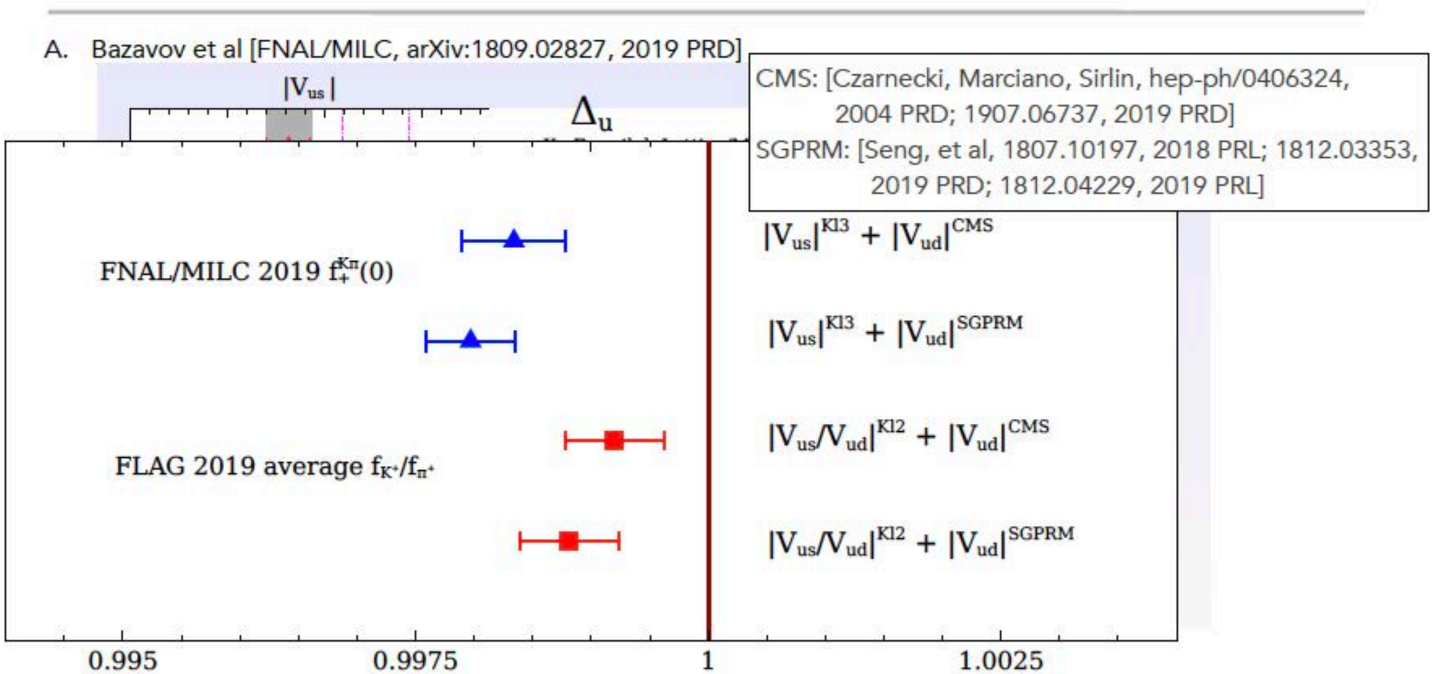


- Research in heavy flavors is an essential component of the current and future particle physics program
- Importance of anomalies
- Important role of the lattice QCD in this physics program

RF2 (1) - Precision SM test in K decays

Vus from $K \to \pi \ell \nu$ and inference from unitarity of CKM

Aida El-Kadra



Tensions with leptonic determinations:

- $\Gamma^{\mathrm{exp}}_{K_{\ell 2}} + f_{K^\pm}$: 1.6σ
- $\Gamma^{\mathrm{exp}}_{K_{\ell 2}} + f_{K^\pm}/f_{\pi^\pm} + |V_{ud}|$: 2.2σ

Tension with CKM unitarity: 2-5σ

Rare καον decays

RF/SNOWMASS21-RF2_RF0-012.pdf
RF/SNOWMASS21-RF2_RF0-124/125.pdf
RF/SNOWMASS21-RF2_RF1-058.pdf
RF/SNOWMASS21-RF2_RF0-..._Norman_Christ-066.pdf
RF/SNOWMASS21-RF2_RF0-..._Antonin_Portelli-055.pdf

Situation before ICHEP 2020

Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{11}	Exp. BR × 10^{11}
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	< 28 (@ 90% CL)
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	1.5 ± 0.3	< 38
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	8.4 ± 1.0	**<17.8**
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	3.4 ± 0.6	< 300

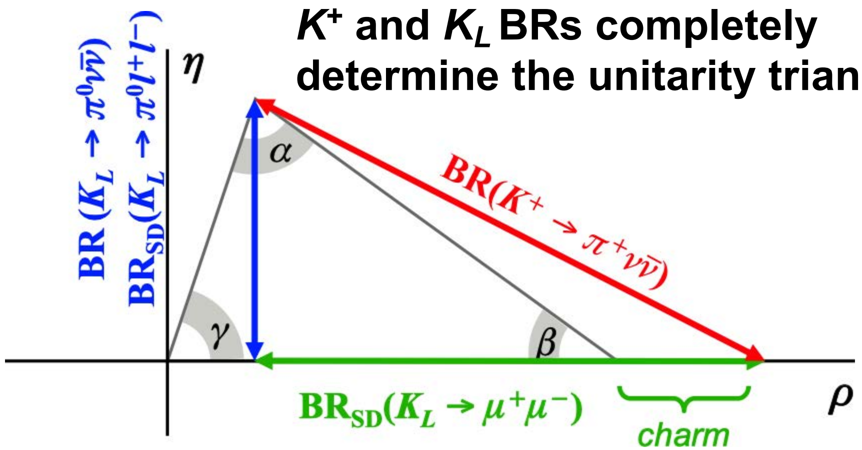
*Approx. error on LD-subtracted rate excluding parametric contributions

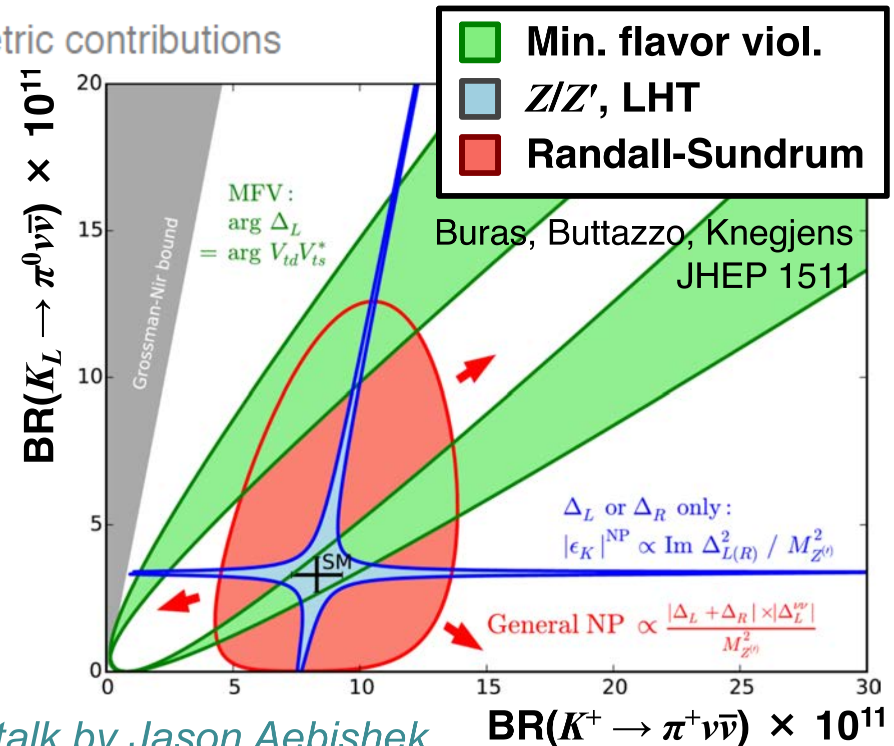
Talks by M. Knecht
D. Guadagnoli
Theory err. under control

→ Plan from lattice QCD
Talk by A. Portelli

Golden channel: $K \to \pi\nu\bar{\nu}$
Very suppressed in the SM, through FCNC
High sensitivity to BSM : corr. K_L and K^+

***K^+ and K_L* BRs completely determine the unitarity triangle**



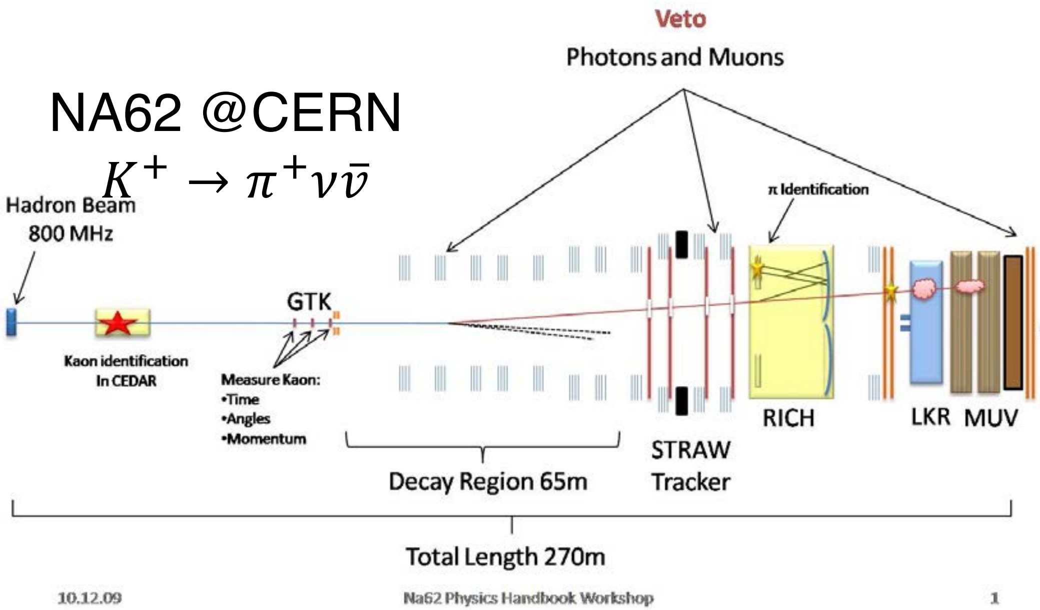


See talk by Jason Aebishek

Experimental landscape

NA62 @CERN

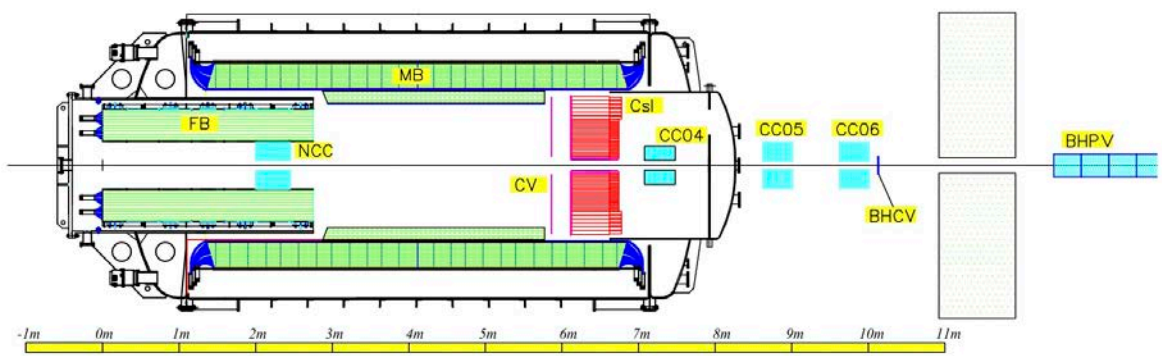
$K^+ \to \pi^+ \nu \bar{\nu}$



Future upgrades in LOI

KOTO @Jparc

$K_L^0 \to \pi^0 \nu \bar{\nu}$



Rare K decay program at LHCb

LHCb experiment:

RF/SNOWMASS21-RF2_RF0_Diego_Martinez_Santos-053.pdf

See talk by Francesco Dettori

- LHCb expanding its physics reach towards strange physics complementary to the core program
- Encouraging Run 1-2 results on $K_S^0 \to \mu^+\mu^-$ and $\Sigma^+ \to p\mu^+\mu^-$
- Large samples available on tape
- Run 2 giving new results with improved trigger
- Upgrade trigger ➡ unprecedented sensitivities on many channels
- Complementary to K_L and K^+ dedicated experiments

LHCb major player for K_S and hyperons rare decays

Sensitivity Studies ArXiv:1808.03477

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K_S^0 \to \mu^+\mu^-$	1	1.0 (1.0)	1.8 (1.8)	~ 3.0	~ 8.0
$K_S^0 \to \pi^+\pi^-$	1	1.1 (0.30)	1.9 (0.91)	~ 2.5	~ 7.0
$K_S^0 \to \pi^0\mu^+\mu^-$	1	0.93 (0.93)	1.5 (1.5)	~ 35	~ 45
$K_S^0 \to \gamma\mu^+\mu^-$	1	0.85 (0.85)	1.4 (1.4)	~ 60	~ 60
$K_S^0 \to \mu^+\mu^-\mu^+\mu^-$	1	0.37 (0.37)	1.1 (1.1)	~ 1.0	~ 6.0
$K_L^0 \to \mu^+\mu^-$	~ 1	2.7 (2.7) $\times 10^{-3}$	0.014 (0.014)	~ 3.0	~ 7.0
$K^+ \to \pi^+\pi^+\pi^-$	~ 2	9.0 (0.75) $\times 10^{-3}$	41 (8.6) $\times 10^{-3}$	~ 1.0	~ 4.0
$K^+ \to \pi^+\mu^+\mu^-$	~ 2	6.3 (2.3) $\times 10^{-3}$	0.030 (0.014)	~ 1.5	~ 4.5
$\Sigma^+ \to p\mu^+\mu^-$	~ 0.13	0.28 (0.28)	0.64 (0.64)	~ 1.0	~ 3.0
$\Lambda \to p\pi^-$	~ 0.45	0.41 (0.075)	1.3 (0.39)	~ 1.5	~ 5.0
$\Lambda \to K_S^0 \to \mu^+\mu^-$	~ 0.45	0.32 (0.31)	0.88 (0.86)	–	–
$\Xi^- \to \Lambda\mu^-\bar{\nu}_\mu$	~ 0.04	39 (5.7) $\times 10^{-3}$	0.27 (0.09)	–	–
$\Xi^- \to \Sigma^0\mu^-\bar{\nu}_\mu$	~ 0.03	24 (4.9) $\times 10^{-3}$	0.21 (0.068)	–	–
$\Xi^- \to p\pi^-\pi^-$	~ 0.03	0.41(0.05)	0.94 (0.20)	~ 3.0	~ 9.0
$\Xi^0 \to p\pi^-$	~ 0.03	1.0 (0.48)	2.0 (1.3)	~ 5.0	~ 10
$\Omega^- \to \Lambda\pi^-$	~ 0.001	95 (6.7) $\times 10^{-3}$	0.32 (0.10)	~ 7.0	~ 20

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K_S^0 \to \pi^+\pi^-e^+e^-$	1	1.0 (0.18)	2.83 (1.1)	~ 2.0	~ 10
$K_S^0 \to \mu^+\mu^-e^+e^-$	1	1.18 (0.48)	2.93 (1.4)	~ 2.0	~ 11
$K^+ \to \pi^+e^-e^+$	~ 2	0.04 (0.01)	0.17 (0.06)	~ 3.0	~ 13
$\Sigma^+ \to pe^+e^-$	~ 0.13	1.76 (0.56)	3.2 (1.3)	~ 3.5	~ 11
$\Lambda \to p\pi^-e^+e^-$	~ 0.45	$< 2.2 \times 10^{-4}$	~ 17 (< 2.2) $\times 10^{-4}$	–	–

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K_S^0 \to \mu^+e^-$	1	1.0 (0.84)	1.5 (1.3)	~ 3.0	~ 8.0
$K_L^0 \to \mu^+e^-$	1	3.1 (2.6) $\times 10^{-3}$	13 (11) $\times 10^{-3}$	~ 3.0	~ 7.0
$K^+ \to \pi^+\mu^+e^-$	~ 2	3.1 (1.1) $\times 10^{-3}$	16 (8.5)$\times 10^{-3}$	~ 2.0	~ 8.0

$\mathcal{R}$ = ratio of production

ϵ = ratio of efficiencies

Next Generation experiments:

- Required to make a precision measurement $K^+ \to \pi^+ \nu\bar{\nu}$ and to make a significant observation of $K_L \to \pi^0 \nu\bar{\nu}$
  - Would become a very high priority if hints of new physics from NA62 or KOTO
  - In absence of hints, more precise measurements ⇨ potential discovery

- **High intensity K^+ and K_L beams at SPS, CERN :** **RF/SNOWMASS21-RF2_RF0-010.pdf**
  3 phases with same primary beamline and interchangeable detectors
  1. "NA62x4": $K^+ \to \pi^+\nu\nu$
  2. KLEVER: $K_L \to \pi^0\nu\nu$
  3. Intermediate stage: K_L beam + charged-particle tracking/PID: $K_L \to \pi^0\lambda^+\lambda^-$; LFV and radiative K_L decays

See talk by Matthew Moulson

- **KOTO Step-2** **RF/SNOWMASS21-RF2_RF0_Y.W.Wah-065.pdf**
  - construction around 2025 and ~100 events at SM level with S/N~1 (3y data).
  - Two major upgrades 2:
    - Higher kaon flux: reduce targeting angle from 16 degrees to 5 degrees, increase target length from 60 mm to 102 mm
    - Increase detector acceptance: increase calorimeter radius from 2 m to 3 m, increase fiducial region from 2 m to ~15 m

See talk by Elizabeth Worcester

Remarks

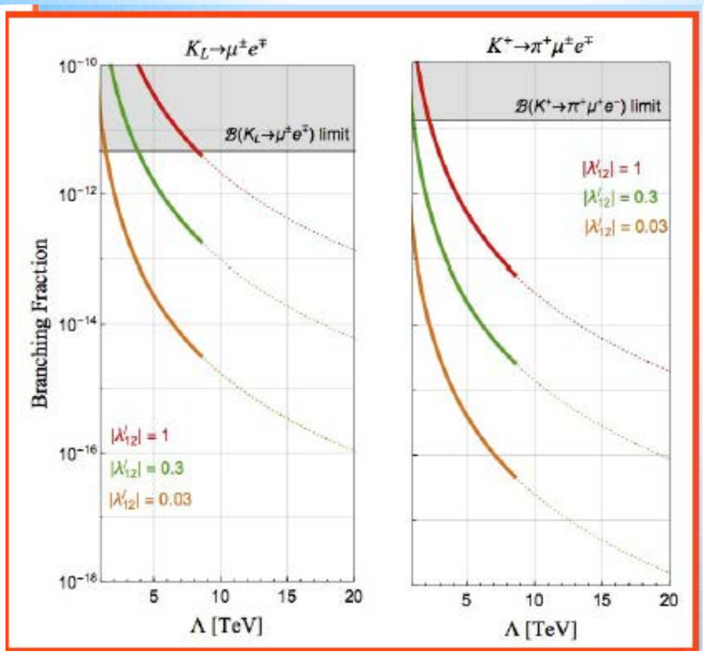
- Synergy with SM tests of in beauty and charm decays (the K triangle)

- Complementary LF violation measurements

- *Especially interesting examples include*

$$K \rightarrow \pi \nu \bar{\nu} \qquad K \rightarrow (\pi)\mu e$$

Diego Guadagnoli at
https://indico.fnal.gov/event/45713/



$K^+ \to \pi^+ \mu^+ e^-$ INSPIRE search

$\Gamma(K^+ \to \pi^+ \mu^+ e^-)/\Gamma_{total}$ Γ_{43}/Γ

E865

Test of lepton family number conservation.

VALUE (10^{-10})	CL%	DOCUMENT ID	TECN	CHG
< 0.13	90	1 SHER 2005	RVUE	+

Very rich physics program at η and η' factories

See talks by Sergi-Gonzalez Solis and Sean Tulin in RF6

RF/SNOWMASS21-RF6_RF2_Sean_Tulin-117.pdf
RF/SNOWMASS21-RF2_RF0_Sergi-085.pdf

Standard Model highlights
- Theory input for light-by-light scattering for $(g\text{-}2)_\mu$
- Extraction of light quark masses
- QCD scalar dynamics

Fundamental symmetry tests
- P,CP violation
- C,CP violation

[Kobzarev & Okun (1964), Prentki & Veltman (1965), Lee (1965), Lee & Wolfenstein (1965), Bernstein et al (1965)]

Dark sectors (MeV—GeV)
- Vector bosons
- Scalars
- Pseudoscalars (ALPs)

(Plus other channels that have not been searched for to date)

Channel	Expt. branching ratio	Discussion
$\eta \to 2\gamma$	39.41(20)%	chiral anomaly, η–η' mixing
$\eta \to 3\pi^0$	32.68(23)%	$m_u - m_d$
$\eta \to \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$	χPT at $O(p^6)$, leptophobic B boson, light Higgs scalars
$\eta \to \pi^0\pi^0\gamma\gamma$	$< 1.2 \times 10^{-3}$	χPT, axion-like particles (ALPs)
$\eta \to 4\gamma$	$< 2.8 \times 10^{-4}$	$< 10^{-11}$[52]
$\eta \to \pi^+\pi^-\pi^0$	22.92(28)%	$m_u - m_d$, C/CP violation, light Higgs scalars
$\eta \to \pi^+\pi^-\gamma$	4.22(8)%	chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation
$\eta \to \pi^+\pi^-\gamma\gamma$	$< 2.1 \times 10^{-3}$	χPT, ALPs
$\eta \to e^+e^-\gamma$	$6.9(4) \times 10^{-3}$	theory input for $(g-2)_\mu$, dark photon, protophobic X boson
$\eta \to \mu^+\mu^-\gamma$	$3.1(4) \times 10^{-4}$	theory input for $(g-2)_\mu$, dark photon
$\eta \to e^+e^-$	$< 7 \times 10^{-7}$	theory input for $(g-2)_\mu$, BSM weak decays
$\eta \to \mu^+\mu^-$	$5.8(8) \times 10^{-6}$	theory input for $(g-2)_\mu$, BSM weak decays, P/CP violation
$\eta \to \pi^0\pi^0\ell^+\ell^-$		C/CP violation, ALPs
$\eta \to \pi^+\pi^-e^+e^-$	$2.68(11) \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to \pi^+\pi^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to e^+e^-e^+e^-$	$2.40(22) \times 10^{-5}$	theory input for $(g-2)_\mu$
$\eta \to e^+e^-\mu^+\mu^-$	$< 1.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \pi^+\pi^-\pi^0\gamma$	$< 5 \times 10^{-4}$	direct emission only
$\eta \to \pi^\pm e^\mp \nu_e$	$< 1.7 \times 10^{-4}$	second-class current
$\eta \to \pi^+\pi^-$	$< 4.4 \times 10^{-6}$ [53]	P/CP violation
$\eta \to 2\pi^0$	$< 3.5 \times 10^{-4}$	P/CP violation
$\eta \to 4\pi^0$	$< 6.9 \times 10^{-7}$	P/CP violation

Gan, Kubis, Passemar, ST [arxiv:2007.00664]

Summary of RF2 LOIs

20 LOIs for which RF2 is primary
4 LOIs for which RF2 is secondary
Split evenly between η(') factories, K physics, light quark physics

Conclusions

A vibrant experimental program was presented, with deep connections with beyond SM phenomenology and a synergistic interaction with the lattice QCD community.
For more details:

https://indico.fnal.gov/event/45713/timetable/#20201002

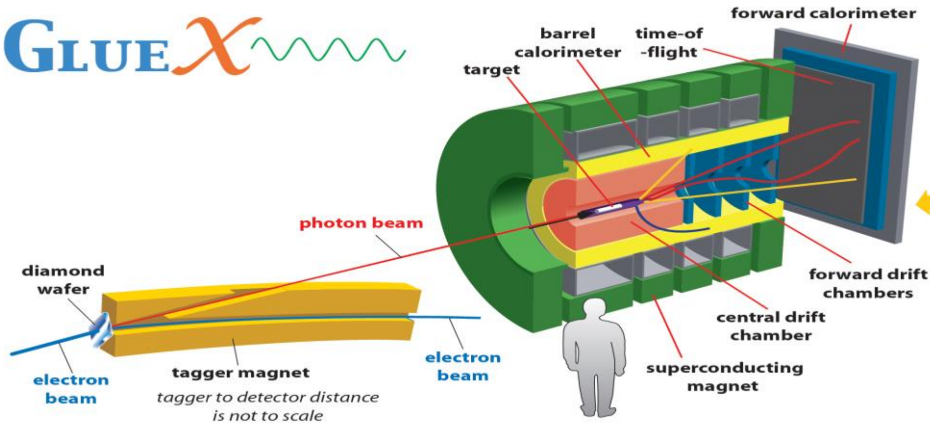
Additional information in back-up

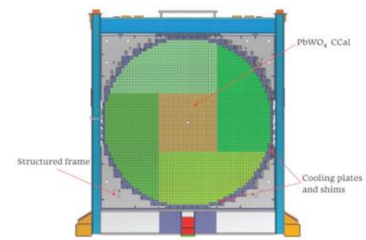
THE END

Jefferson Eta Factory (JEF) experiment γ beam (10 GeV) on H target

GlueX + upgraded forward calorimeter at Jefferson Lab (Hall D)

RF/SNOWMASS21-RF2_RF0_Liping_Gan-017.pdf



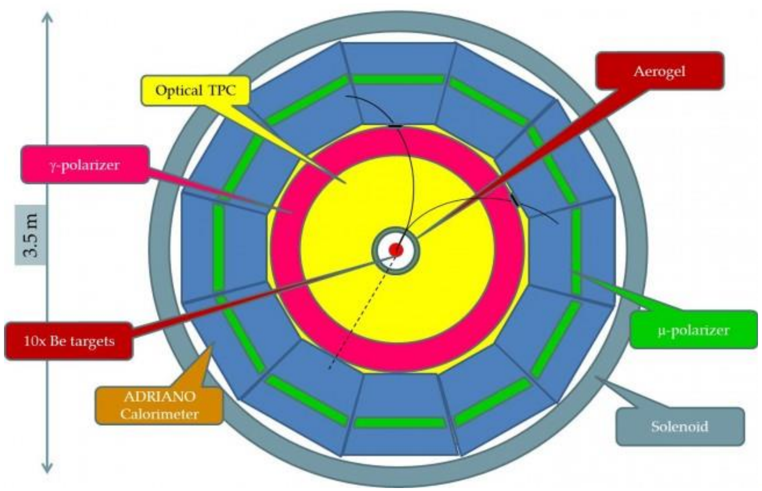


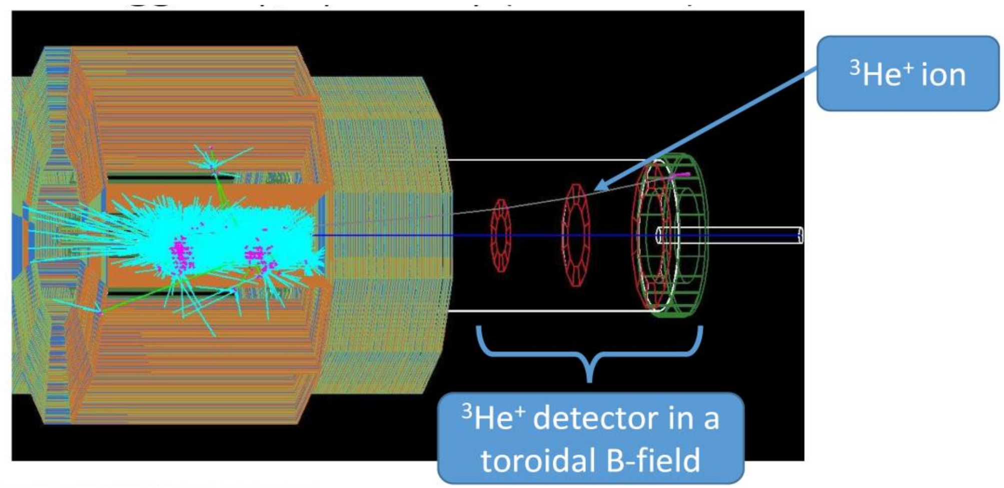
FCAL-II

See talk by Lipin Gan

Rare Eta Decays with a TPC for Optical Photons (REDTOP)

Proton beam (1-3 GeV) on nuclear target (Be/D) RF/SNOWMASS21-RF2_RF6-IF6_IF3_REDTOP_Collaboration_-_new-083.pdf





See talk by Anna Mazzacane

Next Generation experiments:

See talks by Matthew Moulson and Elizabeth Worcester

- **Fermilab based experiment?**
  - Well-developed proposals exist
  - Could be enabled by planned upgrades to Fermilab accelerator complex

  Potential Snowmass message from Rare & Precision Frontier: *design FNAL upgrades to facilitate a broad physics program*

- **Examples of opportunities for discussion and high-level cooperation:**
  - Detector ideas and R&D: Calorimeters with photon vectoring; in-beam vetoes; signal processing and readout
  - Simulation: Benchmarking for MC and event generators; techniques for generation of large samples

- **Message from US Kaon LOI**: Both out of intellectual interest and a desire to maintain breadth in the US physics program, the US kaon physics community would like to explore possibilities for expanded US participation in the current and next-generation rare kaon decay experiments at JPARC and CERN. We would also like to hold open the possibility for more major contributions to these experiments or for a complementary US-based experiment if the science points in that direction.

RF/SNOWMASS21-RF2_RF0_Worcester-092.pdf

See talk by Elizabeth Worcester

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RF/SNOWMASS21-RF2_RF0_Worcester-092.pdf

See talk by Elizabeth Worcester

KOTO experiment:

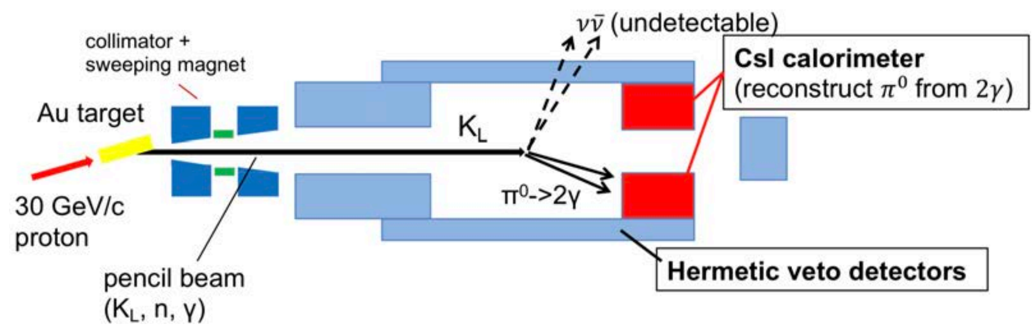
See talk by Elizabeth Worcester

- Limit based on 2015 data:

$$BR\left(K_L \to \pi^0 \nu\bar{\nu}\right) < 3.0\times10^{-9}\,(90\%\ \text{C.L.})$$

No events observed in signal region

$K_L \to \pi^0\nu\bar{\nu}$: ($\pi^0 \to$) 2γ + nothing



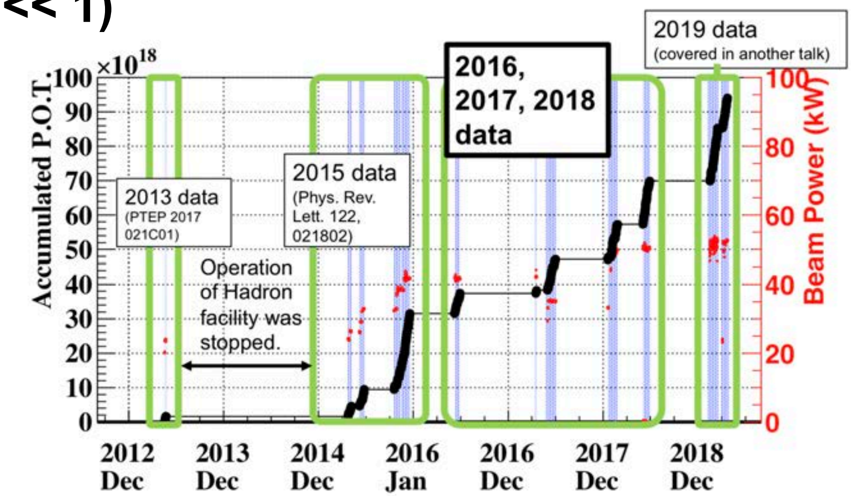
- Blind analysis of 2016-2018 data:

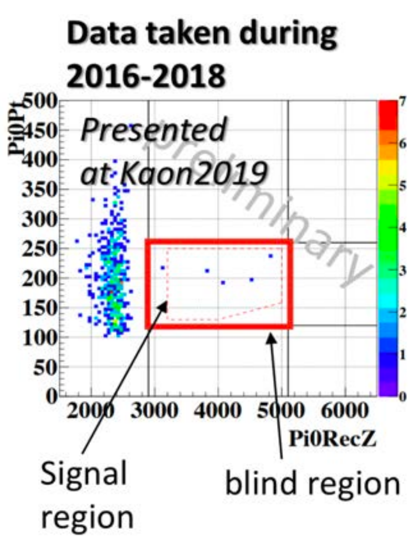
4 events in the signal region (expected << 1)

*1 event from mistake in cut application

*Additional background from charged kaon decay identified

*Upstream detector needed to veto K^+: Prototype installed for 2020 run and Design in progress for higher efficiency UCV



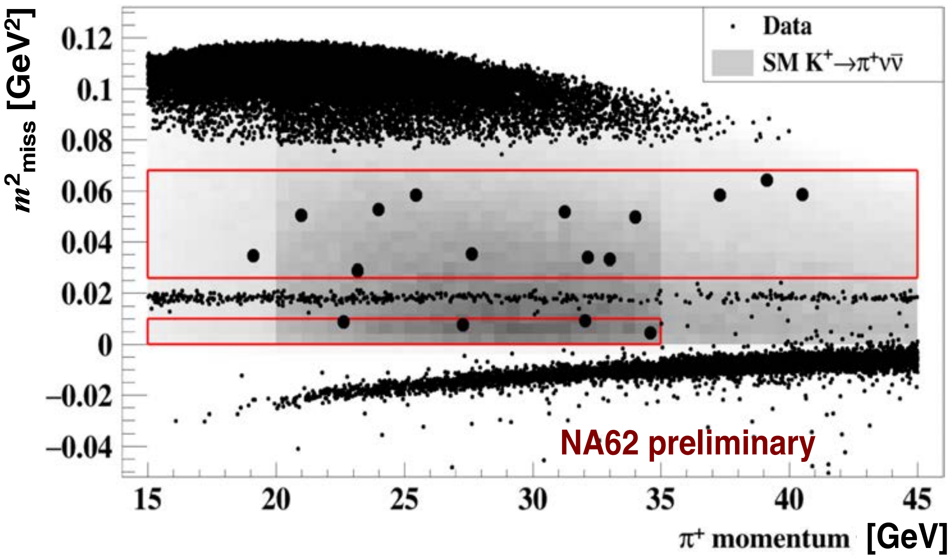


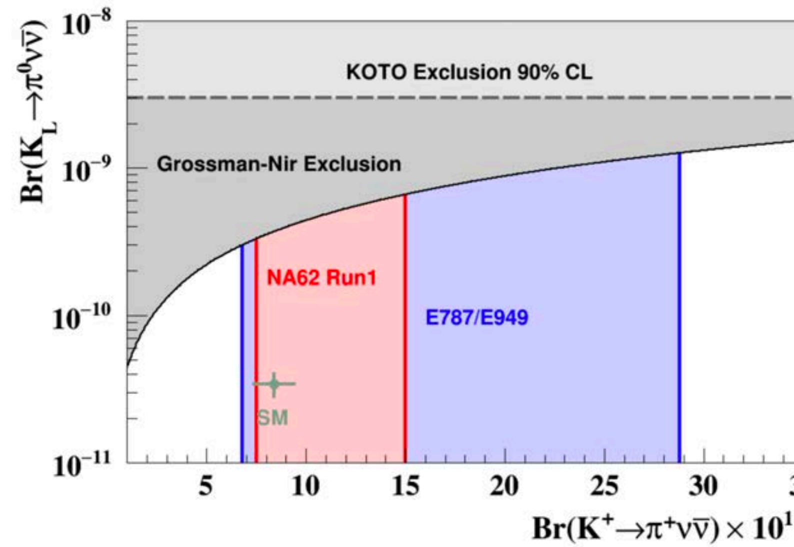
KOTO Step-1 expects to reach SM single event sensitivity by 2025

Plots from Shinohara, KAON 2019 and Shimizu, ICHEP 2020

Preliminary NA62 results, ICHEP2020

With 2018 data





NA62 experiment:

See talk by Matthew Moulson

- Run 1 (2016-2018) : $\mathrm{BR}(K^+ \to \pi^+\nu\nu) = (11.0\ ^{+4.0}_{-3.5\ \mathrm{stat}} \pm 0.3_{\mathrm{syst}}) \times 10^{-11}$

  Expected signal (SM): 10 events, Expected background: 7 events
  Total observed: 20 events, 3.5σ significance

- Plans for NA62 Run 2 (from LS2 to LS3): Data taking resume in July 2021 with
  - Key modifications to reduce background
  - Higher beam intensity: 70% → 100%

Expect to measure BR($K^+ \to \pi^+\nu\nu$) to better than 20%